COMPUTATIONAL EVALUATION OF THE LAGUNA FOIL/PLASMA IMPLOSION EXPERIMENTS*

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I. Introduction

The Laguna foil implosion experiments are part of the Los Alamos foil implosion project, Trailmaster. In the Laguna experiments we are fielding a system that should provide implosion energies of the order of 100 kJ. The Laguna pulse power system consists of a Mark IX helical generator, a 100-nH storage inductor which includes a post-hole convolute design, an explosively-formed fuse opening switch, a surface discharge closing switch, and a vacuum powerflow channel. The imploding plasma is initiated from a 2-cm high, 5-cm radius, 250-nm thick, unbacked aluminum foil.[1] Figure 1 shows a blue print of the Laguna system exclusive of the Mark IX generator.

The purpose of the opening/closing switch combination is pulse shaping. The capacitor bank requires some 135 μs to put a 450 kA seed current into the generator. The generator then has a run time of about 210 μs. We wish to switch current to the imploding load in about 1 μs.

We have examined and optimized the performance of the Laguna system with circuit and 0-D, slug, implosion calculations. The behavior of the foil and plasma prior to the actual pinch was modeled with 1-D, Lagrangian, MHD calculations. The effects of magnetically driven Rayleigh-Taylor instabilities were examined with 2-D Eulerian calculations. The impact of the plasma radiation on the Laguna power flow channel and vacuum interface was examined with the use of a 3-D view factor code. Finally, the question of magnetic insulation of the power flow channel was addressed with 2-D, particle-in-cell, calculations.

II. Circuit and Zero-Dimensional Modeling Results

The 1-D Lagrangian, MHD, code RAVEN contains a circuit modeling capability and a 0-D slug option. The load can be optimized using the 0-D calculations and the 0-D implosion provides a dL/dt voltage pulse for the rest of the circuit model. This has allowed us to make quick, inexpensive, calculations to optimize timings and examine the sensitivity of the system to many possible problems.

Our circuit includes time dependent inductance and resistance values for the Mark IX generator[2] We find that the 1.5 mF (equivalent when Marxed) capacitor bank at firing point 88 will seed the generator in 135 μs. The generator will then feed up to 12 MA into the system which is approximately 131 nH prior to switching. The combination of the explosively formed fuse[3] and the surface discharge switch[4] will transfer 5.5 MA to the load in 1 μs.

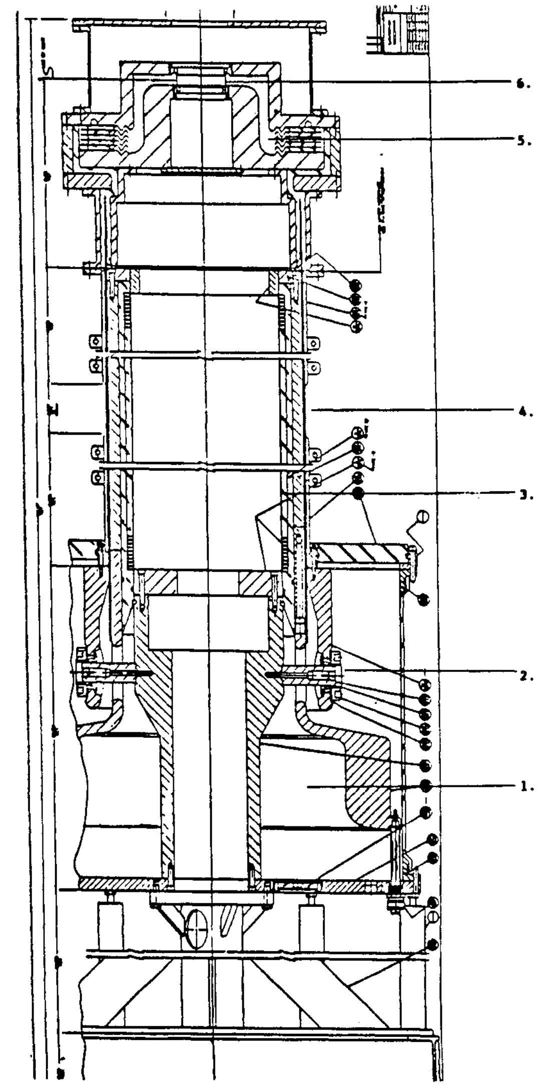

Fig. 1. Blueprint of the tower (upright) portion of the Laguna system: (1) storage inductance; (2) posthole convolute region; (3) explosively formed fuse; (4) surface discharge closing switch; (5) vacuum powerflow chamber; and (6) foil load.

We terminate the 0-D slug implosion when the ratio of the initial radius to the imploding radius reaches 10:1. This 10:1 point will be reached in 1.1 μs from the time that the current first reaches the foil load. At this time the 4.3 μg aluminum plasma will have a velocity of 24 cm/μs or a kinetic energy of 120 kJ. Our experience indicates that stopping these calculations at the 10:1 implosion ratio will overestimate the energy that is given off as radiation when the imploding plasma thermalizes.

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III. MHD Calculations of the Laguna Implosions

We perform MHD calculations with 1-D Lagrangian and 2-D Eulerian codes. The 1-D calculations permit us to track the radii, temperatures, densities and radiation output from the Lagrangian zones from room temperature, solid density foil through the run in of the plasma. These results provide the initial conditions for the 2-D calculations and radiation fluence for the ablation studies.

Figure 2 shows the 1-D implosion. This implosion time is identical to the zero dimensional result and we do not use the 1-D results beyond the 10:1 implosion ratio set as the limit for the 0-D calculations. The 1-D simulation reaches this 10:1 point in 1.13 μs. The 2-D calculations indicate that instabilities may be important well before the 10:1 point is reached.

Figure 3 shows the calculated temperatures as functions of time. The zones of aluminum will vaporize and then ionize during the 340.2 to 340.8 μs period. After this time the plasma is basically isothermal with its temperature increasing from 4 eV up to about 12 eV by 341.3 μs. The temperatures of the zones then jump rapidly as the plasma pinches. During this spike the plasma is no longer isothermal. We have capped the temperature rise in Fig. 3 at 100 eV because we doubt that the actual temperatures will exceed this value. The effect of the instabilities will be to spread out the time over which the kinetic energy is released as radiation. This will lower the effective temperature of the radiation.

The behavior of the plasma temperature is explained by its radiation properties. When the plasma is isothermal and its temperature is relatively low it is optically thin. During this time the energy depositied through Joule heating is quickly radiated away. When the plasma becomes optically thick the energy is trapped and this rapidly drives up the temperature.

We have carried out 2-D Eulerian MHD calculations to examine the growth of magnetically driven Rayleigh-Taylor instabilities. The initial setup for these 2-D calculations is illustrated in Fig. 4. The baseline 1-D simulation for all of our 2-D results was made some time ago and involved an earlier model of the Mark IX generator. For this reason, t = 0.0 for the 2-D simulations corresponds to the point t = 319.72 μs in this, earlier, 1-D simulation.

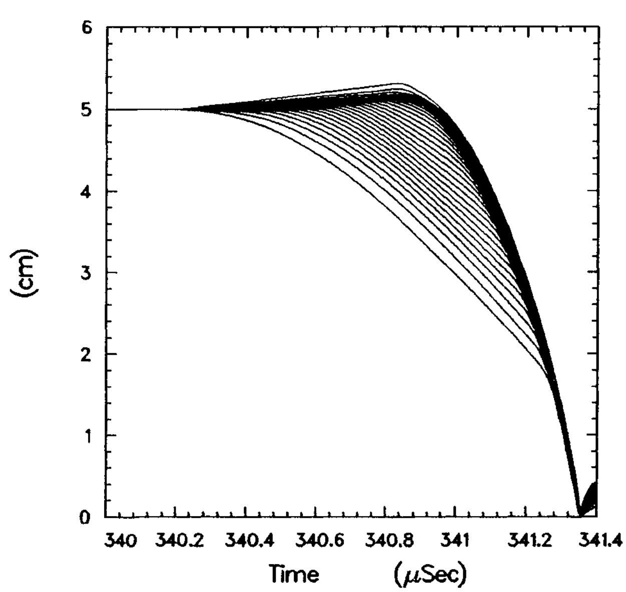

Fig. 2. Implosion history predicted by a 1-D Lagrangian, MHD, code.

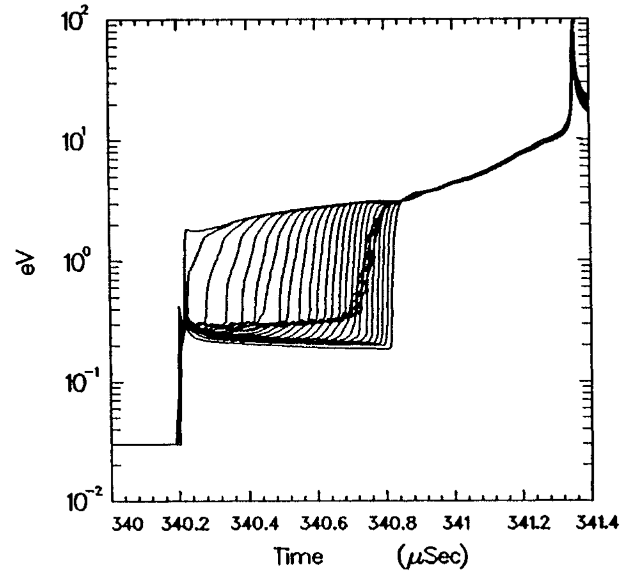

Fig. 3. time history of the temperatures of the Lagrangian zones from the 1-D, MHD, calculation. This graph is arbitrarily capped at 100 eV; a value that is higher than we expect to be reached during the experiment.

Figure 5 shows the breakup of the imploding plasma due to instabilities that have grown from initial, random, density perturbations. A 10% perturbation will lead to a radiation pulse width of the order of 0.25 μs, the 30% level will cause the pulse width to be up to 0.5 μs. Random variations in velocity of 1.0 cm/μs produce instabilities similar to those of the 10% level of density perturbation. The effects of anomalous resistivity have not been included in these simulations.

In our 1-D calculations the vast majority of the radiation output occurs over about a 0.02 μs period. Figure 6 shows material, kinetic and radiation energies for the 30% initial perturbation calculation. As Fig. 5 shows, by 0.3 μs into this calculation the bulk of the plasma has been disrupted at three points. As the connecting material in these regions thins its reduced density leads to an increased magnetic acceleration relative to the denser surrounding material. The velocity of this low density material that is thrown forward is in the range of 60 to 150 cm/μs. The stagnation of this hot, low density plasma corresponds to the increase of radiation output at t $\sim$ 0.28 μs in Fig. 6. The low density plasma continues to accumulate on axis and by t = 0.32 μs the radiation energy output has reached about 30 kJ.

Our calculations indicate that this low density, optically thin plasma is not in local thermodynamic equilibrium (LTE). The ions and electrons have temperatures in the range of a few kiloelectronvolts while the radiation temperature is only a few tens of electronvolts. The later radiation from the denser, optically thick, plasma is in LTE. The 2-D simulations with instabilities predict final peak radiation temperatures in the range from 60 to 80 eV.

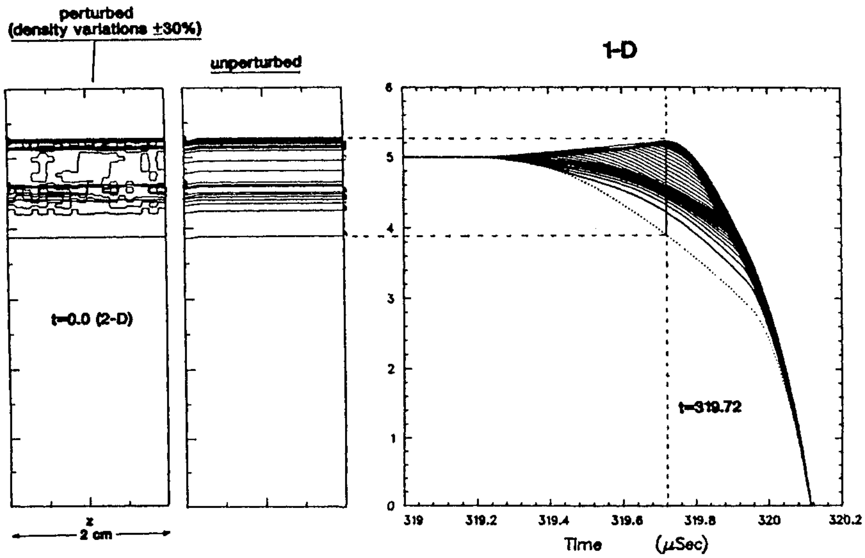

Fig. 4. Initialization of 2-D simulations from a 1-D simulation. The plot on the right shows 1-D Lagrangian cell boundaries as a function of time. The center plot shows density contours for a 2-D unperturbed implosion and the left plot shows density contours where the density has been varied randomly between -30% and +30%.

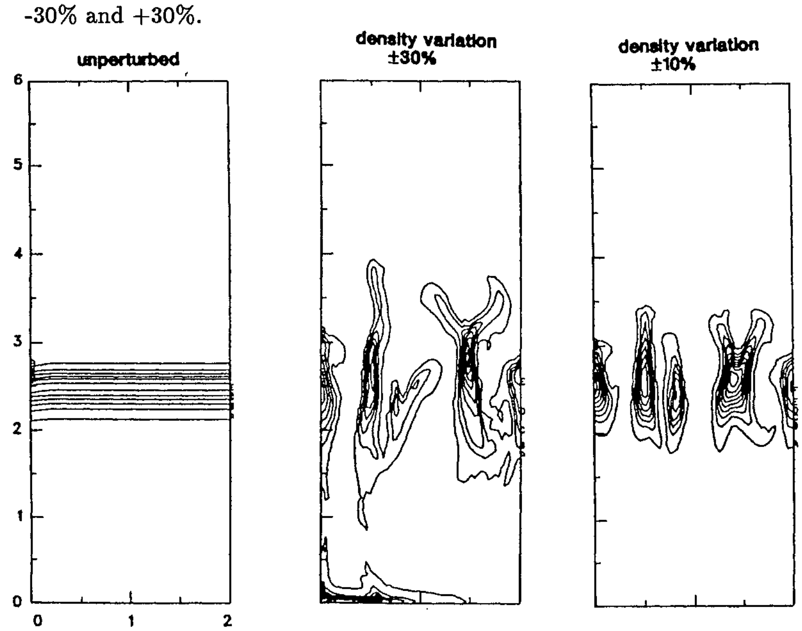

Fig. 5. Contours of constant density for three 2-D simulations at t = 0.3 μs: unperturbed (left); 30% density variation (center); 10% density variation (right).

IV. Power Flow Channel Calculations

Calculations have been done to determine if enough radiation will reach the vacuum insulator to cause flashover, and if radiation induced ablation might cause channel closure.

The radiation flow for the Laguna power flow channel was calculated using the view factor and albedo code GOPHER. The 3-D GOPHER mesh contains 2020 quadrilaterals resulting in over 4 million view factors. Due to the cylindrical symmetry of the problem it can be reduced to the 2-D planar slice shown in Fig. 7. The insert in this figure is a detail of the insulator section. The indicated regions were included to benchmark the albedos with light intensity attenuation measurements. The middle of the insulator stack is not included and the vane structure is mocked up by lowering the albedo of the surface of the cylinder. We used albedos of 0.3 for the anodized aluminum cathode, 0.75 for bare aluminum anode.

We took the view factors calculated by GOPHER, together with time integrated flux from our 1-D code, to calculate the energy per unit area striking the vacuum insulator surface. Reference 4 indicates that a fluence of 50–60 μJ/cm^2 is required to cause insulator flashover. This value is not reached until 341.35 μs.

To determine if ablative closure is a problem, we have chosen a 1 cm long test surface on the cathode indicated by an asterisk in Fig. 7. We multiply the fraction of radiation striking this surface by the output flux and impose this flux on a planar geometry calculation, again using RAVEN.

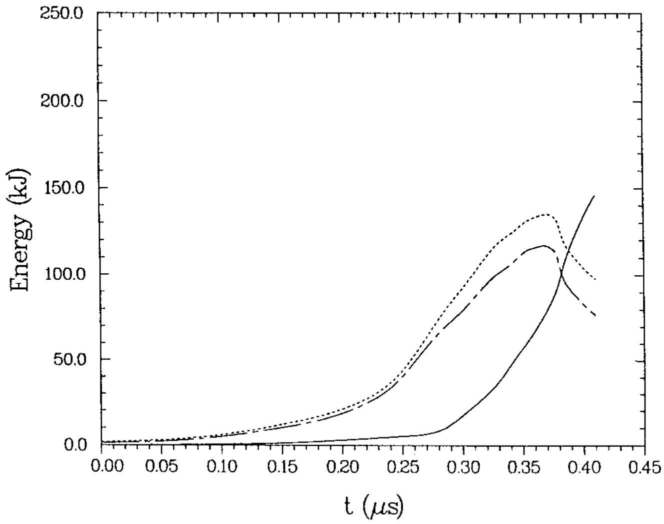

Fig. 6. Energy contained in the material (dotted line), kinetic energy (dash-dot line) and radiation energy output (solid line) for the 2-D (30% perturbation) simulation.

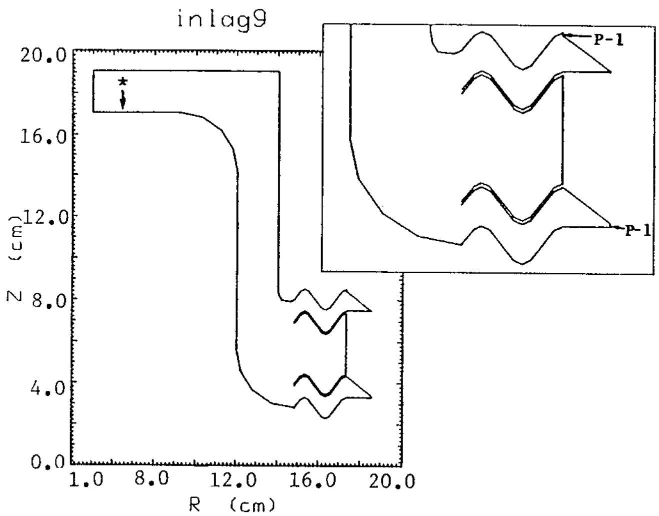

Fig. 7. Two-dimensional Planar Slice of the 3-D zoning.

Two test cases were run; one with a pure aluminum surface, the other with a 0.1 mm layer of a hydrocarbon on the aluminum surface. The zonal resolution of the zone exposed to the radiation, was under 1 micron. In the pure aluminum calculation the ablation front does not expand as much as 1 cm above the surface. We consider the 1 cm point to be important because it is half of the channel width. In the hydrocarbon coated case the 1 cm point is reached at 341.3 μs and this could cause a power flow problem.

To examine the question of magnetic insulation of the powerflow channel, we have made calculations with the 2-D particle-in-cell (PIC) code ISIS. The computer time required to simulate the 1 μs load current pulse would be prohibitive. We have, therefore, set up a "steady state" problem with representative conditions. We have included in this calculation the region of the powerflow channel from the radiation baffles up through the narrowing of the throat. Then, we have mocked up the impedance of the remaining channel, about 25 mΩ. Into this modified setup, we launched a TEM wave with sufficient voltage that we achieved a steady state voltage of 85 kV across the channel when it was conducting 3.4 MA. These are conditions similar to those expected approximately 0.8 μs into the current rise in the load.

We made two calculations to examine the behavior of electrons under these conditions. In the first a low density of electrons was introduced uniformly throughout the channel every 2000 times steps. The electrons remained essentially stationary, indicating that the Lamor radius must be very small.

In the second calculation we permitted emission from the surfaces. In this calculation the electrons were pinned to the cathode surfaces, again indicating magnetic insulated.

ISIS results indicate that in the throat of the powerflow channel we will have a Lamor radius of about 5×10^{-5} cm for electrons and 0.1 cm for ions. Therefore, the channel should be insulated for both. This magnetic insulation should be established before radiation induced ablation becomes a significant problem.

References

1. B. Barthell, V. Gomez, J. Moore, "Thin Foils for JXB Implosions," to be presented at the IEEE Seventh Pulsed Power Conference, Monterey, CA, June 12–14, 1989.
2. C. Fowler and R. Caird, "The Mark IX Generator," ibid.
3. J. Goforth, I. Lindemuth, S. Marsh, R. Reinovsky, "Experiments with Explosively Formed Fuse Opening Switches in Higher Efficiency Circuits," ibid.
4. R. E. Reinovsky, J. H. Goforth, A. E. Greene, and J. Graham, "Characterization of Surface Discharge Switches and High Performance Applications," in Digest of Technical Papers. Sixth IEEE Pulsed Power Conference, Arlington VA, p. 544 (1987).
5. C. L. Enloe and R. E. Reinovsky, "Ultra-Violet Induced Insulator Flashover as a Function of Material Properties," in Digest of Technical Papers, 4th IEEE Pulsed Power Conference, Albuquerque, NM, p. 679 (1983).